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Transfer of Potentially Toxic Elements in the Soil-Plant System in Magnesite Mining and Processing Areas

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Abstract: Mining activities, ore concentrations, and transport processes generate large amounts of pollutants, including hazardous elements, which are released into the environment. This work presents the results of experimental research aimed at evaluating the environmental risks of soil and plant contamination in two magnesite mining and processing areas in the Slovak Republic, and assesses the phytoremediation potential of dominant plant species. Eleven potentially toxic elements in the soil were investigated using X-ray fluorescence spectrometry (Cd, Pb, Cr, Zn, Cu, As, Ni, Mn, Mg, Fe) and atomic absorption spectrometry (Hg). In plants, potentially toxic elements were investigated using inductively coupled plasma mass spectrometry (Cu, As, Cd, Pb) and inductively coupled plasma atomic emission spectrometry (Cr, Zn, Mn, Mg). Selected soil parameters (pH, redox potential, and soil organic matter) were also investigated. Soil contamination was evaluated using environmental indices (geoaccumulation index—I_{geo}, enrichment factor—*EF*, contamination factor—C_f, degree of contamination—C_d). The phytoremediation potential of plants was evaluated using the bioconcentration factor (*BCF*) and the translocation factor (*TF*). The soil reaction in the studied areas indicated a strong alkalization of the soil. The soils in Jelšava-Lubeník were significantly contaminated with Cr, As, Mn, and Mg. The most significant enrichment based on the average values of *EF* was found to be in the order of Cd > Mg > Zn > Cu > As > Cr > Ni > Pb > Fe > Hg > Mn. The observed values of C_f and C_d indicated a high degree of soil contamination. In Košice, the soils were found to be significantly contaminated with Cr, Mn, Mg, and Ni. The most significant enrichment was found in the order of Cd > Mn > Ni > Pb > Zn > Mg > Cu > As > Fe > Cr > Hg. Very high C_f was found for Pb and Cr. The results of correlation and hierarchical cluster analyses suggest a similar origin of pollutants caused by significant anthropogenic interventions due to magnesite mining and processing. The investigated dominant plant species, *Phragmites australis*, *Agrostis stolonifera*, *Elytrigia repens*, and *Taraxacum officinale* are able to accumulate high concentrations of the monitored potentially toxic elements without more serious load or damage. The results of *BCF* and *TF* confirmed that *P. australis* and *T. officinale* appeared to be suitable accumulators in the phytoextraction process. In the case of *E. repens* and *A. stolonifera* it was confirmed that they accumulate and immobilize high concentrations of potentially toxic elements, especially in the roots, establishing the suitability of their use in phytostabilization processes.

Keywords: contamination; environmental indices; phytoremediation

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1. Introduction

Soil contamination by potentially toxic elements currently poses a serious environmental threat and is one of the most pressing global environmental problems [1–4]. Mining activities, ore concentration, and transport processes cause dust and wastewater generation, especially in the immediate vicinity of mines [5]. Tailings, dust emissions, and acid mine drainage cause the release of large amounts of pollutants into the environment, including hazardous elements [6,7]. This can jeopardize soil production capacity, ecological integrity, and habitat security in mining areas [8–11]. Mining, smelting, and industrial processing

of ores are the cause of serious environmental pollution. While the world's population doubled in the second half of the 20th century, the production of the five potentially toxic elements—copper, lead, nickel, tin, and zinc—more than doubled [12].

Potentially toxic elements are ubiquitous in the environment and adversely affect not only ecological systems but also human health [13,14]. The bioavailability of potentially toxic elements in soil depends on specific combinations of chemical, biological, and environmental parameters [15]. The distribution of potentially toxic elements in plants is heterogeneous and is controlled by genetic, environmental, and toxicological factors. The interaction of potentially toxic elements in the plant-soil system depends mainly on the level of soil contamination and the plant species [16]. Physiological and biochemical processes in a plant's life cycle require essential potentially toxic elements such as copper, iron, manganese, nickel, and zinc, which can become toxic if present in excessive amounts [17]. Non-essential potentially toxic elements such as lead, cadmium, arsenic, and mercury are highly toxic and have no significant function in plants. They can cause serious environmental pollution and affect various physiological and biochemical processes in plants [18,19]. Most plant species are unable to adapt to high levels of potentially toxic elements. At increased concentrations of pollutants in soil, some native plants stop growing or even die due to phytotoxicity, suggesting that the plants have different levels of tolerance for potentially toxic elements [20]. There are plants that survive, grow, and multiply in soils contaminated with potentially toxic elements. Most of these species tolerate concentrations of potentially toxic elements and keep them at the roots with minimal translocation to the leaves [21].

Decontamination of soil is a cleaning process that restores it to its original state. This is a relatively complicated and long-term process, since it is almost impossible to completely remove potentially toxic elements from the soil [22,23]. Several remediation approaches have been developed to cultivate soil contaminated with potentially toxic elements. They are primarily based on mechanical or physicochemical techniques. They are limited by high costs and irreversible changes in the physicochemical and biological properties of soils, which can lead to deterioration of the soil ecosystem and secondary pollution [24–27]. From an economic as well as an environmental point of view, biological methods are more beneficial, as they are more environmentally friendly and support the renewal and growth of plants on contaminated soil. In general, bioremediation technologies are more in line with the concept of sustainable development compared to traditional physical and chemical remediation technologies. Bioremediation is a generally accepted method of soil remediation because it is assumed to rely on natural processes [28,29]. An important method of bioremediation is phytoremediation, which is considered a highly efficient and an ecologically and economically advantageous method that can be applied to a large area. It can prevent the spread of contaminants and improve the productive capacity of the soil by releasing various organic substances into the soil [27,30]. It is a method of remediation of soils contaminated with potentially toxic elements by using plants, which extract pollutants from the soil or reduce their bioavailability in the soil. This method is suitable if a wide area is contaminated with pollutants and the substances are in the root zone of the plant, as the plants can absorb potentially toxic elements even at low concentrations through the root system [31–33].

Hyperaccumulators are plant species that can accumulate high levels of potentially toxic elements in their organs without signs of phytotoxicity. Their activity consists of actively absorbing one or several potentially toxic elements from the soil. Potentially toxic elements are not preserved in the roots but move to other parts of the plant [34–37]. To date, more than 450 types of potentially toxic element hyperaccumulators have been identified that can concentrate more than 10 mg/kg mercury, 100 mg/kg cadmium, 1000 mg/kg cobalt, chromium, copper, and lead, and 10,000 mg/kg zinc and nickel [38–40]. Significant hyperaccumulators, according to Ma et al. [41], Schmidt [42], and Scragga [43] are *Thlaspicaerulescens*, *Betula pendula*, *Salix viminalis*, *Zea mays*, *Helianthus annuus*, *Agrostis*

capillaris, *Agrostis stolonifera*, and *Pteris vittata*. Highly resistant plants include *Elytrigia repens* and *Taraxacum officinale* [44].

The aim of this study was to assess the environmental risks of soil and plant contamination in the areas of magnesite mining and processing through environmental indices and to estimate the phytoremediation potential of dominant plant species.

2. Materials and Methods

2.1. Study Area

The research was carried out in the tailings of the magnesite mining and processing area of the Jelšava-Lubeník and Košice mines located in the Revúca and Košice regions. Based on the environmental regionalization of the Slovak Republic, Jelšava (48°38′39.1″ N 20°13′02.7″ E) and Lubeník (48°39′18.3″ N 20°11′48.9″ E) have been included in the Revúca region of the 2nd environmental quality with a slightly disturbed environment. Rendzinas, Cambisols, and Luvisols predominate in this area [45,46]. The climate in the study area is warm, slightly humid, with cold winters. In winter, the average temperature is in the range of −3 to −5 °C and in summer, 14.5 to 16.5 °C. The average annual rainfall is in the range of 700–800 mm [47]. Slovak Magnesite Factory Jelšava and SLOVMAG Lubeník (Figure 1) account for the maximum magnesite production and represent magnesite storage that is expected to last for the next 100 years in Jelšava, and 10 years in Lubeník [48].



Figure 1. Magnesite factory Jelšava-Lubeník (Slovakia).

Another investigated area was near the former magnesite plant and mine in Košice (48°42′50.2″ N 21°15′29.1″ E). According to the environmental regionalization of Slovakia, the studied area in the Košice region belongs to the 3rd degree of environmental quality with a severely disturbed environment. Soil types of Rendzina and Pseudogley predominate in this area [46]. The climate in the Košice region is warm and slightly humid. In January, the average temperature ranges from −3 to 2 °C and in July, from 15 to 26 °C. The average annual rainfall is 530 mm [47]. Dust generated during the processing of magnesite significantly polluted the air in Košice and the city became one of the most polluted cities. At present, the industrial area of the plant and the mine is devastated and dilapidated (Figure 2) [49,50].



(**a**) (**b**)

Figure 2. (**a**) Magnesite factory in Ťahanovce; (**b**) Bankov Mine (Slovakia).

2.2. Sampling Procedure

In Jelšava-Lubeník (JL), 12 sampling points were identified and, in Košice (KE), 10 sampling points were monitored (Figure 3), all classified as agricultural land. Soil sampling was carried out in the years 2019–2021 from the horizon A to a depth of 0.05 to 0.15 m. One homogeneous sample consisted of five random samples taken at regular intervals in one locality and consisted of approximately 1 kg of soil. The samples were placed in plastic bags, transported to the laboratory, cleaned of plant debris and other materials. They were then dried at room temperature, crushed, and sieved through a 2 mm stainless steel sieve. The collection and processing procedures were in accordance with the standard STN ISO 10381-6 [51] and with Decree 338/2005 Coll. from the Ministry of Agriculture of the Slovak Republic [52], which lays down the details of the soil sampling procedure.

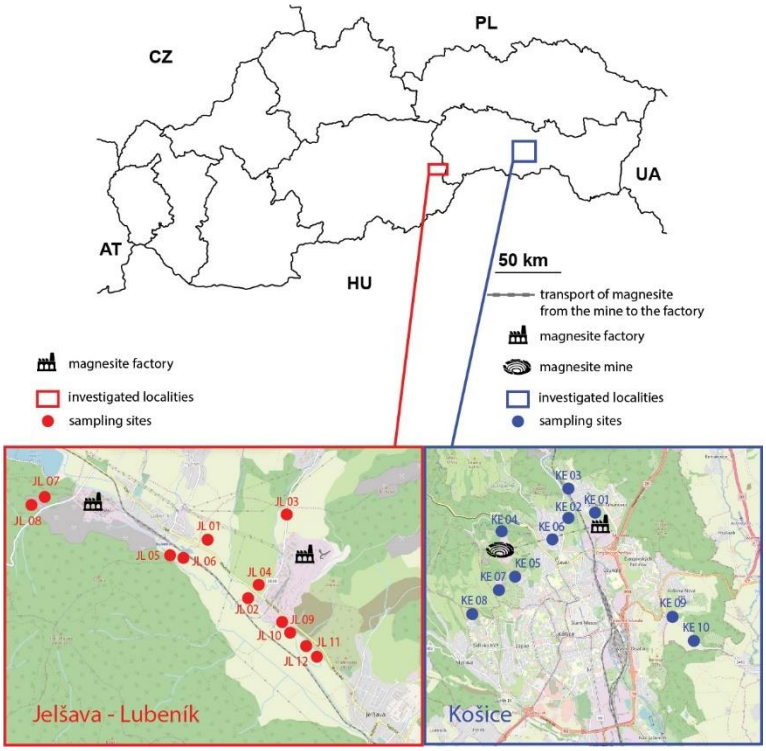


Figure 3. Location of sampling sites in the investigated areas (Slovakia).

The underground and above-ground parts of the dominant plant species, which are present in the investigated localities and form monocultures, were also examined. The species *Phragmites australis*, *Agrostis stolonifera*, and *Elytrigia repens* were collected in Jelšava-Lubeník, while *Elytrigia repens* and *Taraxacum officinale* were sampled in Košice. The samples were placed in plastic bags, transported to the laboratory, washed of residual materials, dried at room temperature, and divided into individual parts (root, stem, flower, and leaf) for further analysis.

2.3. Analytical Methods

Soil reaction (pH), redox potential (Eh), and soil organic matter (SOM) were determined in the soil samples. The pH was determined as the exchange soil reaction in 1M KCl neutral salt solution (20 g of soil mixed with 50 mL of 1M KCl) potentiometrically on a Mettler Toledo pH-meter (Mettler-Toledo Group, Zurich, Switzerland). Redox potential was also measured on a Mettler Toledo instrument. The soil organic matter content was determined by a dry route on a C/N Analyzer (Euro EA 3000, Pavia, Italy) [53].

The content of potentially toxic elements was determined in cooperation with an accredited laboratory (Certificate No. 042/S-004) of the Dionýz Štúr State Geological Institute in Spišská Nová Ves. X-ray fluorescence spectrometry (Cd, Pb, Cr, Zn, Cu, As, Ni, Mn, Mg, Fe) using SPECTRO XEPOS HE X-ray Spectrometer (SPECTRO ANALYTICAL INSTRUMENTS GmbH, Kleve, Germany) and VARIAN VF-60-WS X-ray tube (W-Anode) and atomic absorption spectrometry (Hg) using AMA-254 Mercury Analyzer (ALTEC, Uherské Hradiště, Czech Republic) were used to determine the content of potentially toxic elements in the soil. NIST 2711, NIST 2709, GBW 07404, GBW 07406, and GBW 07405 standards were used to determine potential toxic elements in the soil. The total content of potentially toxic elements in plants was determined using inductively coupled plasma mass spectrometry (Cu, As, Cd, Pb) with an AURORA M90 Spectrometer (BRUKER CAM, Bremen, Germany) and ICP MS 7900 (AGILENT, Santa Clara, CA, USA) and inductively coupled plasma atomic emission spectrometry (Cr, Zn, Mn, Mg) using ICP OES 5100 and ICP OES 5110 Analyzers (AGILENT, Santa Clara, CA, USA) [53]. Standards TM 15.3, TM 25.5, TM 25.6, TM DA 64.3, and GBW 07703 were used to determine potential toxic elements in plants. The obtained values of potentially toxic elements were compared with the limit values for sandy-aluminous soils and for the soil–plant relationship set by Act No. 220/2004 Coll. [54].

Soil contamination was assessed using the following pollution indices: index of geoaccumulation (I_{geo}), enrichment factor (EF), contamination factor (C_f), and degree of contamination (C_d).

The index of geoaccumulation (I_{geo}) makes it possible to determine the level of soil contamination by individual potentially toxic elements on the basis of their concentration in a soil sample and their geochemical background values. I_{geo} was calculated according to Müller [55]: $I_{geo} = log_2(C_n/1.5B_n)$, where C_n represents the content of the selected potentially toxic element in the sample and B_n is the background value of the given potentially toxic element [56]. Based on I_{geo} values, the level of contamination can be characterized as follows: $I_{geo} \leq 0$ (uncontaminated), $0 < I_{geo} < 1$ (uncontaminated to moderately contaminated), $1 \leq I_{geo} < 2$ (moderately contaminated), $2 \leq I_{geo} < 3$ (moderately to heavily contaminated), $3 \leq I_{geo} < 4$ (heavily contaminated), $4 \leq I_{geo} < 5$ (heavily to extremely contaminated), and $I_{geo} \geq 5$ (extremely contaminated).

The enrichment factor (EF), which allows the assessment of the level of anthropogenic activity intensity and the risk of contamination, was calculated according to Buat-Menard and Chesselet [57], using Mn as the reference element: $EF = \frac{c_n\ (sample)}{c_{ref}(sample)} / \frac{B_n(background)}{B_{ref}(background)}$, where c_n (sample) is the content of the investigated potentially toxic element in the studied environment, c_{ref} (sample) is the content of the reference element in the investigated environment, B_n (background) is the content of the examined potentially toxic element in the benchmark environment, and B_{ref} (background) is the content of the reference element in the benchmark environment. The values can be interpreted as

follows: $EF < 2$ (deficiency to minimal enrichment), $2 < EF < 5$ (moderate enrichment), $5 < EF < 20$ (significant enrichment), $20 < EF < 40$ (very high enrichment), and $EF > 40$ (extremely high enrichment).

The contamination factor (C_f) and degree of contamination (C_d), which determine soil quality and soil contamination level based on the average content of potentially toxic elements, were calculated according to Håkanson [58]: $C_f = \frac{C_i}{B^i_n}$, where C_i is the average content of the selected potentially toxic element in the sample and $B^i{}_n$ is the background value of the given potentially toxic element for soils SR [56]. The interpretation of C_f values is as follows: $C_f < 1$ (low contamination), $1 \leq C_f < 3$ (moderate contamination), $3 \leq C_f < 6$ (considerable contamination), and $C_f > 6$ (very high contamination). The sum of all contamination factors of the individual potentially toxic elements expresses the degree of contamination (C_d): $C_d = \sum_{i=1}^{n} C_f$, where C_f represents the contamination factor of the selected potentially toxic element and n is the number of analyzed elements. C_d values are classified as follows: $C_d < 8$ (low degree of contamination), $8 \leq C_d < 16$ (moderate degree of contamination), $16 \leq C_d < 32$ (considerable degree of contamination), and $C_d > 32$ (very high degree of contamination) [58].

Within plant species, their phytoremediation ability was investigated using the bioconcentration factor (*BCF*) and translocation factor (*TF*). The *BCF* expresses the ability of plants to accumulate potentially toxic elements and was determined according to Baker [59]: $BCF = = \frac{C_v}{C_n}$, where C_v represents the content of the selected potentially toxic element in the chosen part of the plant and C_n is the content of the potentially toxic element in the soil sample. The values are evaluated as follows: $BCF < 1$ (excluder, the potentially toxic element is immobilized in the root), $BCF = 1$ (indicator, the content of the potentially toxic element in the plant reflects the situation in the external environment), and $BCF > 1$ (accumulator, the potentially toxic element is concentrated in the above-ground parts of the plant). The *TF* allows quantifying the part of the plant where the selected potentially toxic element is dominantly accumulated [60]: $TF = \frac{C_{ag}}{C_{ug}}$, where C_{ag} is the content of the selected potentially toxic element in the above-ground part of the plant and C_{ug} is the content of the selected potentially toxic element in the underground part of the given plant species. If the *TF* value is < 1, the selected potentially toxic element tends to accumulate in the underground parts of the plant. If $TF > 1$, the selected potentially toxic element accumulates predominantly in the above-ground parts of the plant and the plant is deemed to be a potentially suitable accumulator in phytoremediation.

The results were logarithmically transformed and statistically processed using IBM SPSS Statistics 26, where descriptive statistics and correlation analysis were resorted to, and PAST 4, where a hierarchical cluster analysis (HCA) and principal component analysis (PCA) were performed.

3. Results and Discussion

3.1. Soil Reaction, Soil Organic Matter, and Total Content of Potentially Toxic Elements in Soil

Soil response is one of the factors that play an important role in the retention, mobilization, and migration of potentially toxic elements in soil [61–63]. According to Fuller [64], in acidic soils (pH 4.2–6.6), the elements Cd, Ni, and Zn are highly mobile, Cr is moderately mobile, and Cu and Pb are practically immobile. While in neutral to alkaline soils (pH 6.7–7.8), Cr is highly mobile, Cd and Zn are moderately mobile, and Ni is immobile. Increased mobility makes potentially toxic elements available to plants, resulting in greater toxicity. The pH values in Jelšava-Lubeník ranged from 7.0 to 9.3, indicating that the soils in the study area are neutral to strongly alkaline (Table 1). In Košice, the pH values ranged from 5.3 to 9.1, showing that the soils in this area are strongly acidic to strongly alkaline. Similar findings are reported in the studies of Yang et al. [65], Štofejova et al. [66], Fazekaš et al. [67], and Hronec and Adamišin [68], who confirmed a strong alkalization of the soil in the areas of magnesite mining and processing.

Table 1. Measured content of potentially toxic elements in soil (mg/kg) and selected soil parameters in Jelšava-Lubeník (Slovakia) and Košice (Slovakia) expressed by descriptive statistics.

Study Area	Parameter	Mean	Median	Minimum	Maximum	Standard Deviation	Limit Value *
Jelšava-Lubeník	Cr	157.08	104.50	78.00	793.00	141.99	70.00
	As	25.81	20.50	11.00	84.00	15.36	25.00
	Mn	1348.94	1307.50	400.00	2817.00	478.76	2.10–95.27 **
	Mg	30,411.94	18,605.00	8400.00	113,400.00	24,493.51	200.00–400.00 **
	Hg	0.07	0.06	0.01	0.14	0.03	0.50
	Cd	0.44	0.40	0.40	1.00	0.12	0.70
	Pb	29.61	30.50	16.00	45.00	6.77	70.00
	Zn	82.61	82.00	52.00	113.00	14.76	150.00
	Cu	27.64	26.50	13.00	64.00	11.41	60.00
	Ni	31.92	29.50	19.00	54.00	9.14	50.00
	Fe (%)	4.17	4.32	2.20	6.40	0.92	2.64 **
	pH/KCl	8.20	7.90	7.00	9.30	0.91	-
	Eh (mV)	147.00	133.00	38.00	230.00	52.40	-
	SOM (%)	3.69	3.33	1.27	6.28	1.66	-
Košice	Cr	155.70	82.00	59.00	682.00	181.60	70.00
	As	19.80	19.50	8.00	32.00	7.58	25.00
	Mn	994.85	947.00	512.00	1500.00	286.09	2.10–95.27 **
	Mg	16,828.35	9580.00	3855.00	90,300.00	23,827.98	200.00–400.00 **
	Hg	0.29	0.16	0.08	0.98	0.28	0.50
	Cd	0.45	0.45	0.40	0.50	0.05	0.70
	Pb	42.45	32.00	23.00	239.00	46.63	70.00
	Zn	91.45	89.50	51.00	219.00	38.03	150.00
	Cu	41.95	31.00	16.00	108.00	27.12	60.00
	Ni	56.80	31.00	14.00	573.00	121.65	50.00
	Fe (%)	2.89	2.91	1.50	5.04	0.75	2.64 **
	pH/KCl	6.90	7.40	5.30	8.10	0.95	-
	Eh (mV)	167.00	174.00	−6.00	274.00	80.75	-
	SOM (%)	1.88	1.91	0.83	2.96	0.57	-

Notes: * Act No. 220/2004 Coll. of Laws [54], ** average values for Slovakia [53], Eh—redox potential, SOM—soil organic matter.

The current research clearly confirms the key role of organic carbon in the sorption of inorganic contaminants [69–71]. SOM values in Jelšava-Lubeník ranged from 3.33 ± 1.66% (median ± standard deviation), which means that the humus supply in the soils is medium to very acceptable. SOM values in Košice ranged from 1.91 ± 0.57% (median ± standard deviation), which means that the humus supply in soils is very small to acceptable (Table 1).

The total content of potentially toxic elements in Jelšava-Lubeník and Košice, expressed by descriptive statistics, is given in Table 1. The maximum value of Cr in Jelšava-Lubeník exceeded the legal limit value by 11.33 times and in Košice by 9.74 times. Zhong et al. [72] state that the toxic effect of As in soil is several times higher than that of other potentially toxic elements, and thus increases environmental risks and makes it necessary to pay increased attention to remediation processes. In Košice, the maximum measured value of Ni exceeded the legal limit value by 11.46 times. Limit values for Mn and Mg are not set by law in Slovakia. The average value of Mn in soils in the Slovak Republic is in the range of 2.10–95.27 mg/kg [53]. The maximum value of Mn found in Jelšava-Lubeník was 2817 mg/kg and in the territory of Košice, 1500 mg/kg; Kabata-Pendias [22] states that if the content of Mn in the soil exceeds 1500 mg/kg, toxicity can occur. Average Mg values for Slovak soils are in the range of 200–400 mg/kg. The measured values of Mg in the investigated areas exceeded the average values for the Slovak Republic by several times, while the maximum measured value in Jelšava-Lubeník exceeded the average value by 567 times, and in Košice by 451 times. These findings are consistent with previous studies by Fazekaš et al. [67], Štofejova et al. [66], and Štofejová et al. [73], who found significant

soil contamination with these potentially toxic elements in the studied areas, resulting in the formation of $Mg(OH)_2$ crusts and alkalization and salinization of the soil.

The average content of Hg, Cd, Pb, Zn, Cu, and Ni in Jelšava-Lubeník did not exceed the limit values of these potentially toxic elements set by law in the monitored period [54]. In Košice, the average content of As, Hg, Cd, Pb, Zn, and Cu did not exceed the statutory limit values.

3.2. Assessment of Soil Pollution

Soil pollution in Jelšava-Lubeník and Košice was evaluated using environmental indices (Tables 2 and 3 and Figure 4). In Jelšava-Lubeník, the geoaccumulation index (I_{geo}) of Hg, Pb, Ni, Mn, and Fe reached a value lower than 1, indicating a minimal anthropogenic effect evaluated as uncontaminated to moderately contaminated [55]. The same was true for Zn, Cu, and As, with the exception of one site in relation to Zn (JL08), one site in relation to As (JL07), and two sites in relation to Cu (JL09, JL10), where I_{geo} was assessed as moderately contaminated ($1 < I_{geo} < 2$). Additionally, in the case of Cr, I_{geo} was < 1, except for one site (JL07), where I_{geo} was evaluated as moderately to heavily contaminated. Moderate to heavy contamination ($2 < I_{geo} < 3$) was recorded for Cd in all sites. In the case of Mg, the I_{geo} values were in the range of 0.61–3.31. These values were evaluated as uncontaminated to heavily contaminated. Based on the average I_{geo} values, the content of potentially toxic elements increases in the order of Mn < Hg < Fe < Pb < Ni < Cr < As < Cu < Zn < Mg < Cd. The enrichment factor (*EF*) makes it possible to assess the intensity level of anthropogenic activities, and if *EF* values are < 2, the minimum enrichment can be attributed to natural causes or to the fluctuation of the content of potentially toxic elements in the soil [57]. Significant enrichment ($5 < EF < 20$) was confirmed for Cd and Mg in almost all localities. For other elements, values ranged from deficiency or minimal enrichment ($EF < 2$) to moderate enrichment ($2 < EF < 5$). The most significant enrichment based on the average values of *EF* was found in the order of Cd > Mg > Zn > Cu > As > Cr > Ni > Pb > Fe > Hg > Mn.

Table 2. The index of geoaccumulation (I_{geo}) and enrichment factor (*EF*) for potentially toxic elements in the soil in Jelšava-Lubeník (Slovakia).

Area	Hg		Cd		Pb		Cr		Zn		Cu	
	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*
JL 01	−0.29	1.52	2.42	9.94	−0.34	1.45	−0.45	1.36	0.44	2.50	−0.33	1.52
JL 02	−0.46	2.52	2.42	18.58	−0.53	2.39	−0.31	2.79	0.26	4.15	−0.30	2.81
JL 03	−0.87	1.32	2.42	12.52	−0.01	2.34	−0.43	1.74	0.50	3.33	0.44	3.18
JL 04	0.04	2.06	2.68	12.82	0.06	2.05	−0.44	1.45	0.45	2.68	0.42	2.73
JL 05	−0.76	1.46	2.42	13.19	−0.26	2.06	0.08	2.61	0.88	4.57	−0.32	1.98
JL 06	−0.09	1.77	2.68	13.03	−0.06	1.81	0.40	2.48	0.99	3.74	0.01	1.90
JL 07	−0.85	1.04	2.86	13.75	−0.70	1.14	2.00	7.32	0.82	3.28	0.80	3.57
JL 08	−0.87	1.66	2.42	17.41	−0.75	1.93	0.15	3.61	1.01	6.87	0.53	5.18
JL 09	−1.87	0.59	2.61	10.88	−0.77	1.05	−0.36	1.36	0.75	3.00	1.07	3.69
JL 10	−0.37	1.46	2.42	8.52	−0.73	0.97	−0.23	1.37	0.75	2.69	1.28	3.93
JL 11	−0.15	1.16	2.42	6.69	−0.32	1.02	−0.53	0.88	0.54	1.84	0.60	1.91
JL 12	0.14	1.20	2.52	6.39	−0.14	0.99	−0.22	0.95	0.68	1.77	0.50	1.60

Area	As		Ni		Mn		Mg		Fe	
	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*
JL 01	−0.58	1.24	−0.54	1.27	−0.88	1	1.18	7.01	−0.78	1.10
JL 02	−0.69	2.14	−0.53	2.39	−1.79	1	0.69	5.61	−1.11	1.59
JL 03	−0.16	2.10	−0.08	2.21	−1.22	1	0.82	4.13	−0.45	1.71
JL 04	0.60	3.22	−0.05	1.92	−0.97	1	0.61	2.99	−0.43	1.48
JL 05	−0.52	1.73	−0.61	1.62	−1.30	1	1.18	5.60	−0.79	1.42

Table 2. *Cont.*

Area	As		Ni		Mn		Mg		Fe	
	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*
JL 06	−0.27	1.56	−0.31	1.52	−0.91	1	1.27	4.56	−0.60	1.24
JL 07	1.44	5.71	0.35	2.42	−0.86	1	1.99	7.24	−0.30	1.53
JL 08	0.41	4.43	0.19	3.72	−1.46	1	0.97	6.16	−0.43	2.55
JL 09	0.72	3.02	0.48	2.45	−0.79	1	2.22	8.32	−0.17	1.56
JL 10	0.76	2.71	0.37	2.08	−0.67	1	2.75	11.18	−0.02	1.57
JL 11	0.10	1.35	−0.23	1.08	−0.33	1	2.94	10.00	−0.20	1.09
JL 12	0.04	1.14	−0.27	0.92	−0.12	1	3.31	10.92	−0.18	0.97

Table 3. The index of geoaccumulation (I_{geo}) and enrichment factor (*EF*) for potentially toxic elements in the soil in Košice (Slovakia).

Area	Hg		Cd		Pb		Cr		Zn		Cu	
	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*
1KE	−5.79	0.01	−0.42	0.57	−0.97	0.39	−1.19	0.33	−1.58	0.25	−3.41	0.07
2KE	−2.84	0.12	−0.42	0.64	−0.89	0.46	−1.33	0.34	−1.12	0.39	−1.34	0.34
3KE	−2.45	0.12	−0.42	0.50	−0.87	0.37	−1.25	0.28	−0.97	0.34	−1.76	0.19
4KE	−0.66	0.73	1.57	3.18	2.54	6.78	2.40	6.07	0.72	1.72	0.30	1.29
5KE	0.15	1.41	1.57	3.67	0.59	1.86	0.80	2.77	−0.12	1.13	−0.22	1.06
6KE	−5.16	0.02	−0.42	0.56	−0.60	0.49	−1.08	0.36	−1.15	0.33	−2.95	0.09
7KE	1.26	2.00	1.57	2.45	0.41	1.09	−0.60	0.53	−0.60	0.54	−0.58	0.54
8KE	−0.59	0.54	1.57	2.34	0.93	1.49	−0.36	0.62	−0.85	0.43	−1.15	0.35
9KE	−0.70	0.75	0.57	1.81	0.03	1.24	−1.24	0.51	0.53	1.77	0.02	1.24
10KE	−1.47	0.24	0.57	1.01	−0.28	0.54	−0.96	0.34	−0.39	0.51	−0.71	0.41
Area	**As**		**Ni**		**Mn**		**Mg**		**Fe**	
	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*	I_{geo}	*EF*
1KE	−1.86	0.22	−0.63	0.50	0.37	1	0.09	0.82	−0.64	0.49
2KE	−1.46	0.31	−0.63	0.56	0.20	1	−0.47	0.62	−0.72	0.52
3KE	−1.50	0.23	−0.52	0.47	0.56	1	−0.31	0.54	−0.47	0.48
4KE	0.19	1.28	1.55	4.82	−0.05	1	1.51	3.43	−0.67	0.65
5KE	−0.53	0.89	−0.71	0.77	−0.30	1	1.33	4.89	−0.95	0.65
6KE	−1.72	0.22	−0.72	0.45	0.41	1	−0.85	0.41	−0.61	0.49
7KE	−0.45	0.60	−0.65	0.52	0.28	1	−0.78	0.47	−1	0.41
8KE	−0.45	0.56	−0.95	0.40	0.35	1	−1.42	0.29	−1.11	0.35
9KE	−0.87	0.66	−0.80	0.69	−0.28	1	−0.17	1.09	−0.84	0.67
10KE	−0.70	0.40	−0.11	0.61	0.58	1	−0.68	0.41	−0.71	0.40

In Košice, I_{geo} achieved values of less than 1 for Zn, Cu, As, Mn, and Fe, which led to its assessment as being uncontaminated to moderately contaminated [55]. This also applied to Hg, Ni, and Mg, except at one site for Hg (KE07), one site for Ni (KE04), and two sites for Mg (KE04, KE05). The I_{geo} for Cd was in the range of −0.42–1.57, which was evaluated as being uncontaminated to moderately contaminated. Moderate to heavy contamination ($2 < I_{geo} < 3$) was confirmed at one site in the case of Pb and Cr (KE04). Based on the average I_{geo} values, the content of potentially toxic elements increased in the order of Hg < Cr < Fe < Cu < As < Mg < Zn < Pb < Ni < Cd < Mn. *EF* values were assessed from deficiency to minimal enrichment in almost all potentially toxic elements at the examined localities. In the case of Cd, Ni, and Mg, values corresponding to moderate enrichment were also found ($2 < EF < 5$). For Pb and Cr, significant enrichment was recorded at one site (KE04; $5 < EF < 20$). Similar findings regarding elevated I_{geo} and *EF* values in mining and industrial areas have been noted in previous studies by Wang et al. [74], Dolezalova-Weissmanova et al. [75], and Fazekašová et al. [76]. The most significant enrichment was found in the order of Cd > Mn > Ni > Pb > Zn > Mg > Cu > As > Fe > Cr > Hg.

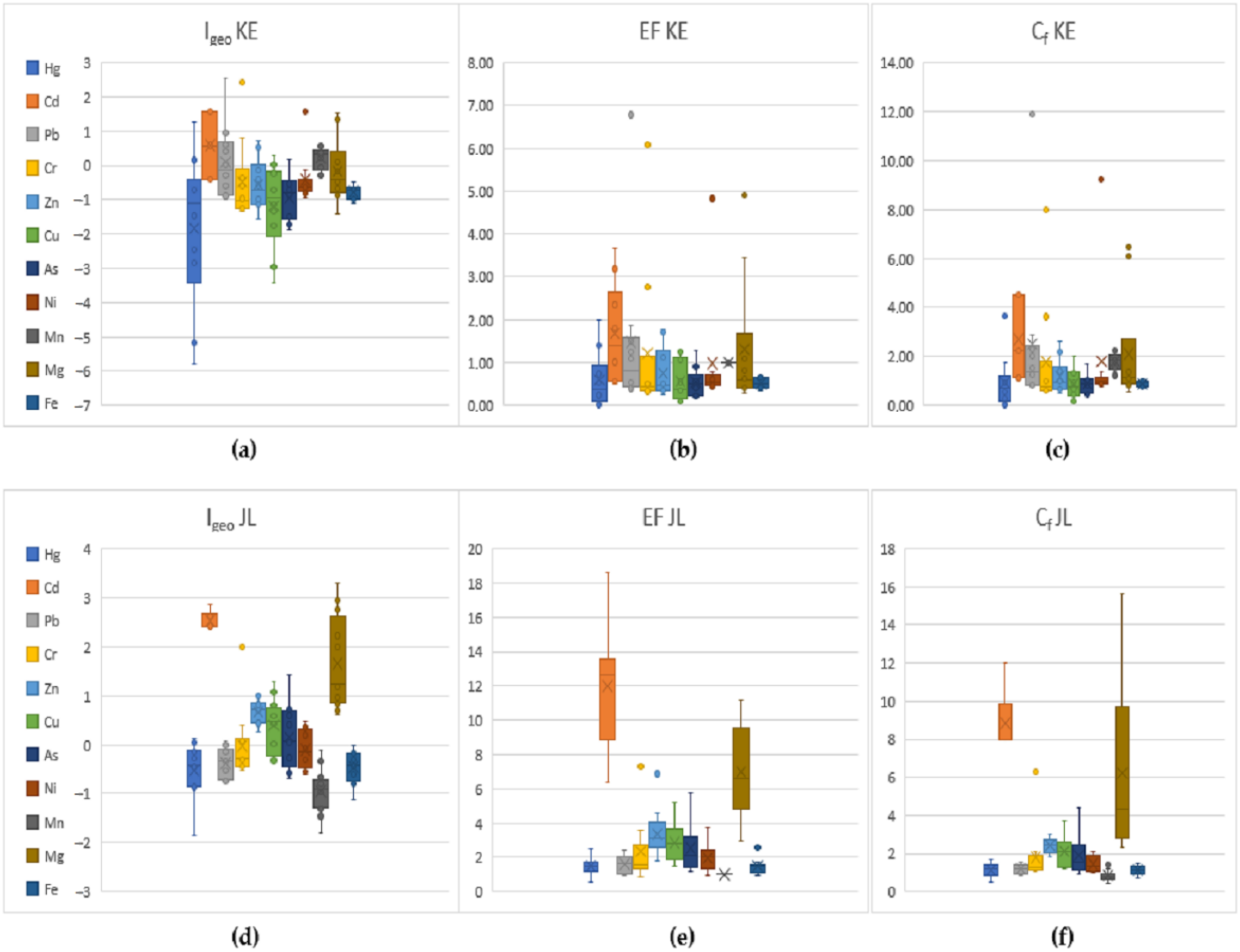


Figure 4. Environmental indices for Jelšava-Lubeník (Slovakia) and Košice (Slovakia): (**a**) index of geoaccumulation (I_{geo}) for Košice; (**b**) enrichment factor (*EF*) for Košice; (**c**) contamination factor (C_f) for Košice; (**d**) index of geoaccumulation (I_{geo}) for Jelšava-Lubeník; (**e**) enrichment factor (*EF*) for Jelšava-Lubeník; (**f**) contamination factor (C_f) for Jelšava-Lubeník.

A very high contamination factor ($C_f \geq 6$) was recorded in all the sites in Jelšava-Lubeník for Cd, in the case of locality JL07, in the order of Cd > Cr (Table 4). In the case of Cu, a considerable contamination factor ($3 \leq C_f < 6$) was recorded in localities JL09 and JL10, for As in JL07, and for Zn in JL08. Moderate contamination levels ($1 \leq C_f < 3$) of the examined potentially toxic elements were recorded in most localities. The degree of contamination was considerable ($16 \leq C_d < 32$) for all sites, except JL01 and JL02, where a moderate degree of contamination was recorded ($8 \leq C_d < 16$). The maximum value was found in JL07 (29.88).

In Košice, the very high contamination factor ($C_f \geq 6$) was found at the site KE04 in the order of Pb > Cr (Table 5). A considerable contamination factor ($3 \leq C_f < 6$) was recorded for Cd at sites KE04 and KE08, at site KE05 in the order of Cd > Cr, and at KE07 in the order of Cd > Hg. A considerable degree of contamination ($16 \leq C_d < 32$) was recorded at KE04 with a value of 31.68. A moderate degree of contamination was found at sites KE05, KE07, KE08, and KE09 ($8 \leq C_d < 16$). A low degree of contamination was recorded at KE01, KE02, KE03, KE06, and KE10.

Table 4. Ranking order of soil contamination in Jelšava-Lubeník according to C_d –value and sequence of the contamination factors (C_f).

					Contamination Factor (C_f)			
					Very High	**Considerable**	**Moderate**	**Low**
			Locality	C_d	$C_f \geq 6$	$3 \leq C_f < 6$	$1 \leq C_f < 3$	$C_f < 1$
Degree of contamination (C_d)	Very high	$C_d \geq 32$						
	Considerable	$16 \leq C_d < 32$	JL 07	29.88	Cd > Cr	As	Cu > Zn	Pb > Hg
			JL 04	20.72	Cd		As > Cu > Zn > Pb > Hg > Cr	
			JL 06	20.62	Cd		Zn > Cr > Cu > Hg > Pb > As	
			JL 10	20.44	Cd	Cu	As > Zn >Hg > Cr	Pb
			JL 09	20.07	Cd	Cu	Zn > As > Cr	Pb > Hg
			JL 08	19.26	Cd	Zn	Cu > As > Cr	Pb > Hg
			JL 12	19.15	Cd		Zn > Cu > Hg > As > Cr > Pb	
			JL 11	17.74	Cd		Cu > Zn > As > Hg > Pb > Cr	
			JL 03	16.97	Cd		Zn > Cu > Pb > AS > Cr	Hg
			JL 05	16.78	Cd		Zn > Cr > Pb > Cu > As	Hg
	Moderate	$8 \leq C_d < 16$	JL 01	15.84	Cd		Zn > Hg > Cu > Pb > Cr > As	
			JL 02	15.34	Cd		Zn > Cu > Cr > Hg > Pb	As
	Low	$C_d < 8$						

Table 5. Ranking order of soil contamination in Košice according to C_d –value and sequence of the contamination factors (C_f).

					Contamination Factor (C_f)			
					Very High	**Considerable**	**Moderate**	**Low**
			Locality	C_d	$C_f \geq 6$	$3 \leq C_f < 6$	$1 \leq C_f < 3$	$C_f < 1$
Degree of contamination (C_d)	Very high	$C_d \geq 32$						
	Considerable	$16 \leq C_d < 32$	KE 04	31.68	Pb > Cr	Cd	Zn > Cu > As	Hg
	Moderate	$8 \leq C_d < 16$	KE 05	15.97		Cd > Cr	Pb > Hg > Zn > Cu > As	
			KE 07	14.20		Cd > Hg	Pb > As > Cu	Cr > Zn
			KE 08	12.22		Cd	Pb > Cr > As > Hg	Zn > Cu
			KE 09	9.90			Cd > Zn > Pb > Cr	Hg > As > Cr
	Low	$C_d < 8$	KE 10	7.79			Cd > Pb > Zn	As > Cu > Cr > Hg
			KE 03	4.58			Cd	Pb > Zn > Cr > As > Cu > Hg
			KE 02	4.57			Cd	Pb > Zn > Cr > As > Cu > Hg
			KE 06	4.21			Cd	Pb > Cr > Zn > As > Cu > Hg
			KE 01	3.64			Cd	Pb > Cr > Zn > As > Cu > Hg

3.3. Correlation and Hierarchical Cluster Analyses

Correlations between potentially toxic elements and selected soil parameters (pH, redox potential—Eh, soil organic matter—SOM) in Jelšava-Lubeník are shown in Table 6. Based on Spearman's rho coefficient at significance levels $p < 0.05$ and $p < 0.01$, significant positive correlations were found between Cr-Zn, As-Cu, As-Ni, As-Fe, Mn-Mg, Mn-Cu, Mn-Fe, Mn-pH, and Mn-SOM, Mg-Fe, Mg-pH, Mg-SOM, and Hg-Pb. Copper positively correlated with Ni, Fe, pH, and SOM. Other correlations was found between Ni-Fe, Fe-pH, Fe-SOM, and pH-SOM. A significantly negative correlation was noted between Hg-Eh, pH-Eh, and Eh-SOM.

For Košice, correlations are shown in Table 7. Only positive significant correlations were found in this area, specifically between Cr-Mg, Cr-Ni, Cr-Fe, and Cr-Eh, between As-Mg, As-Zn, As-Cu, As-Ni, and As-Fe, between Mn-Fe, Mg-Zn, Mg-Cu, Mg-Ni, and Mg-pH, and between Hg-Cu, Pb-Zn, Zn-Cu, Cu-Ni, Cu-Fe, and Ni-Fe. Positive correlations between Mg and pH in magnesite mining and processing areas have also been confirmed in previous studies by Yang et al. [65] and Štofejová et al. [66]. High correlation coefficients between the examined potentially toxic elements may indicate a similar origin of pollution sources, caused by significant anthropogenic interventions due to industrial activities. They can be characterized by a similar process of migration and transformation through physico-chemical environmental conditions. Low or negative correlation coefficients may indicate different sources of pollution that are closely related to natural or geogenic processes [75,77].

Table 6. Correlation matrix (Spearman's rho) between potentially toxic elements and selected soil parameters in Jelšava-Lubeník (Slovakia).

Parameter	As	Mn	Mg	Hg	Cd	Pb	Zn	Cu	Ni	Fe	pH	Eh	SOM
Cr	0.217	−0.189	0.007	−0.205	0.332	−0.266	0.781 **	0.126	0.126	0.014	−0.155	0.347	−0.042
As		0.503	0.343	−0.162	0.465	−0.371	0.340	0.895 **	0.916 **	0.825 **	0.563	−0.200	0.559
Mn			0.902 **	0.349	0.262	−0.126	0.028	0.625 *	0.385	0.811 **	0.739 **	−0.364	0.895 **
Mg				0.187	0.059	−0.322	0.231	0.540	0.217	0.706 *	0.627 *	−0.119	0.783 **
Hg					0.146	0.579 *	−0.223	−0.188	−0.335	0.039	0.291	−0.592 *	0.483
Cd						0.164	0.186	0.233	0.336	0.227	0.232	−0.337	0.387
Pb							−0.301	−0.530	−0.483	−0.385	−0.099	−0.298	−0.175
Zn								0.285	0.231	0.242	−0.134	0.519	0.000
Cu									0.912 **	0.926 **	0.721 **	−0.228	0.642 *
Ni										0.797 **	0.500	−0.116	0.406
Fe											0.768 **	−0.231	0.769 **
pH												−0.702 *	0.838 **
Eh													−0.609 *

Note: * $p < 0.05$, ** $p < 0.01$, Eh—redox potential, SOM—soil organic matter.

Table 7. Correlation matrix (Spearman's rho) between potentially toxic elements and selected soil parameters in Košice (Slovakia).

Parameter	As	Mn	Mg	Hg	Cd	Pb	Zn	Cu	Ni	Fe	pH	Eh	SOM
Cr	0.417	0.249	0.621 **	−0.357	0.347	0.329	0.393	0.350	0.530 *	0.526 *	−0.142	0.648 *	−0.139
As		−0.109	0.527 *	0.192	−0.252	0.118	0.462 *	0.613 **	0.779 **	0.478 *	0.028	0.207	0.335
Mn			−0.130	−0.173	0.278	0.022	−0.308	−0.106	0.084	0.484 *	−0.288	0.315	0.012
Mg				0.041	0.225	0.211	0.721 **	0.591 **	0.602 **	0.415	0.634 *	0.188	−0.236
Hg					−0.182	−0.344	0.277	0.575**	0.097	0.056	0.272	−0.549	0.598
Cd						0.150	0.165	0.096	−0.043	0.104	.	.	.
Pb							0.524 *	0.073	−0.035	0.018	0.012	0.286	−0.012
Zn								0.745 **	0.439	0.345	0.431	−0.055	0.236
Cu									0.574 **	0.488 *	0.283	−0.030	0.261
Ni										0.699 **	0.160	0.224	0.285
Fe											−0.028	0.427	0.378
pH												−0.234	−0.258
Eh													−0.382

Note: * $p < 0.05$, ** $p < 0.01$, Eh—redox potential, SOM—soil organic matter.

A dendrogram of the hierarchical cluster analysis of potentially toxic elements is shown in Figure 5 for Jelšava-Lubeník and in Figure 6 for Košice. The hierarchical cluster analysis identified several groups of associations between potentially toxic elements in relation to the area and confirmed that the elements in one group are associated with the same pollution source. In Jelšava-Lubeník, the first group consisted of the elements Cd-Hg, the second group of elements Mg-Fe, the third group solely of Mn, the fourth group of Zn-Cr, and the fifth group of Pb-Cu, Ni, As. Five groups were also identified in Košice. The first group consisted of Cd-Hg, the second group of Mg-Fe, the third group of Mn, the fourth group of Zn-Cr, and the fifth group of As-Cu, Ni, and Pb. The correlation analysis of the Jelšava-Lubeník area and the Košice area also identified similar relationships between potentially toxic elements, which may indicate mainly anthropogenic sources of the origin of potentially toxic elements in the soil. The high content of Mn, Mg, and Fe can come from the weathering of basic materials but also from anthropogenic sources, which are related to the intensity of mining and processing of magnesite. Similar findings have also been reported by Dolezalova-Weissmanova et al. [75] and Štofejová et al. [66].

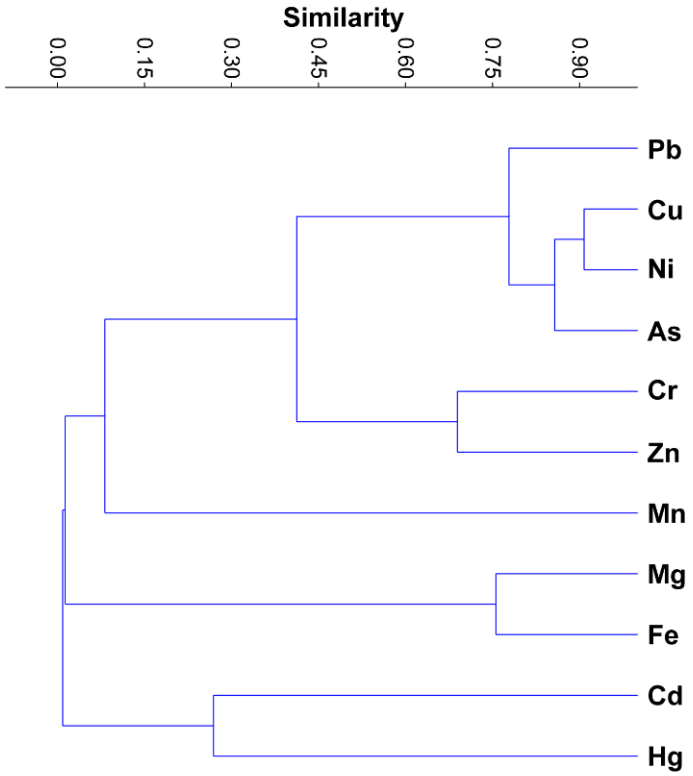


Figure 5. Dendrogram derived from hierarchical cluster analysis (HCA) of the potentially toxic elements in Jelšava-Lubeník (Slovakia).

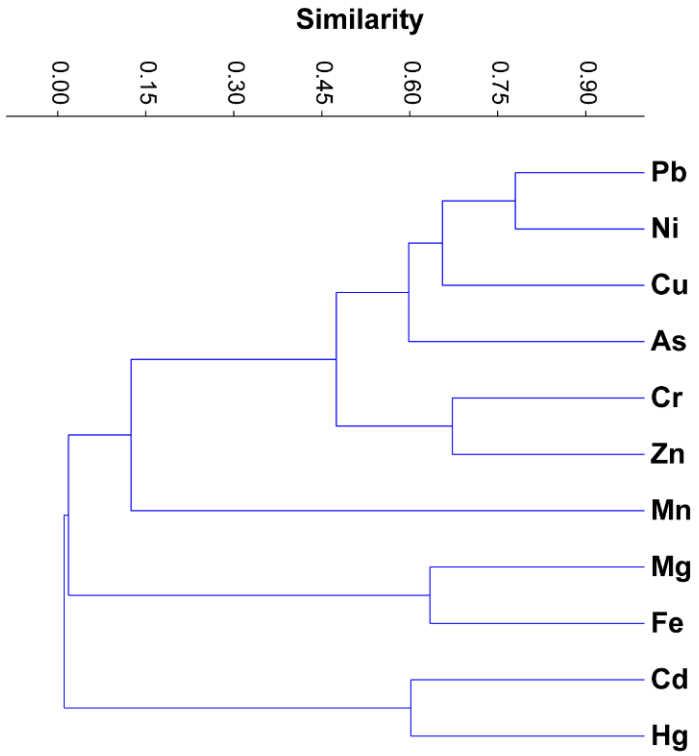


Figure 6. Dendrogram derived from hierarchical cluster analysis (HCA) of the potentially toxic elements in Košice (Slovakia).

3.4. Total Content of Potentially Toxic Elements in Plants

The total content of potentially toxic elements in the above-ground and underground parts of plants is recorded in Figure 7 for *Elytrigia repens*, *Agrostis stolonifera*, and *Phragmites australis* in Jelšava-Lubeník, and in Figure 8 for *Elytrigia repens* and *Taraxacum officinale* in Košice. The Cd content exceeded the legal limit [54] in the roots of *E. repens* (0.25 mg/kg of dry matter) and *A. stolonifera* (0.12 mg/kg of dry matter). The measured Pb values exceeded the limit values in all plant species, with the highest content recorded in the roots of *E. repens* (16.20 mg/kg of dry matter) and *A. stolonifera* (13.10 mg/kg of dry matter). The maximum value exceeded the limit value by 162 times. These findings are confirmed by Siedlecka et al. [78], who state that Pb tends to accumulate in plant roots and is toxic. Similar findings for Cd, Cr, and Pb are reported by Minkina et al. [79]. Although Zn is an essential component for plants, it can cause toxicity at high concentrations [80]. The Zn content exceeded the statutory values for all examined plants, with the highest content being found in *E. repens* roots (46.00 mg/kg of dry matter), *P. australis* flowers (43.90 mg/kg of dry matter), and *A. stolonifera* roots (35.30 mg/kg of dry matter). The highest measured value exceeded the limit value by 23 times. The law does not set any limit values for Cr, but Allen [81] states that it is toxic to plants at concentrations higher than 0.50 mg/kg. In Jelšava-Lubeník, Cr values were in the range of 1.20–14.30 mg/kg, while the highest measured value was in the roots of *E. repens*. In the case of Košice, Cr values were in the range of 2.20–27.50 mg/kg, with the highest content in *T. officinale* roots. The measured Cu values exceeded the limit values for all plants in Košice, while the highest measured values were in the roots *of E. repens* (31.70 mg/kg of dry matter) and *T. officinale* (30.80 mg/kg of dry matter). Yruela [82] states that, although Cu is necessary for plant growth, it has toxic effects at elevated levels. The increased Cu content in plants is attributed not only to natural origins but also to anthropogenic activities, such as mining, smelting, ore processing, and agriculture, as a result of which Cu is released into the environment. The measured As values exceeded the limit values set by law by several times. The highest As content was found in the roots of *T. officinale* (4.20 mg/kg of dry matter) and *E. repens* (3.11 mg/kg of dry matter), which is consistent with the study by Williams et al. [83], who report that As is taken up and allocated predominantly in plant roots. The average Mn content in plants in Jelšava-Lubeník was 103.11 mg/kg with the highest content in *E. repens* roots (337.00 mg/kg of dry matter) and in Košice 90.70 mg/kg with the highest content also in *E. repens* roots (183.00 mg/kg of dry matter). Kabata-Pendias and Mukherjee [84] report that Mn is toxic to plants at 500 mg/kg, with some types of hyperaccumulators being able to accumulate up to 10,000 mg/kg. The Mg content in Jelšava-Lubeník was in the range of 2420.00–17,400.00 mg/kg, with the highest content being found in the order of *E. repens* root > *A. stolonifera* root > *P. australis* flower. In Košice, Mg values were in the range of 682.00–4347.00 mg/kg, while the highest content was found in the order of *T. officinale* leaf > *T. officinale* root > *E. repens* root. The high content of Mg in the investigated plant species in the areas of magnesite mining and processing is also confirmed by previous studies done by Zeleňáková et al. [85], Hronec and Hajdúk [86], and Fazekaš et al. [67]. Based on the obtained results, it is possible to support the claim that the investigated dominant plant species in environmentally polluted areas can accumulate high concentrations of monitored potentially toxic elements without showing more serious burden or damage. It can be stated that these plant species could potentially be used in phytoremediation processes. The results of the bioconcentration factor (BCF) and translocation factor (TF) confirmed that *P. australis* and *T. officinale* appear to be suitable accumulators in the phytoextraction process, as they can not only accumulate potentially toxic elements in the roots but also transport them to the above-ground parts, especially Cd, Cr, and Mg (Figure 9). The bioconcentration factor in *E. repens* and *A. stolonifera* confirmed that these species accumulate and immobilize high concentrations of potentially toxic elements, especially in the roots, which confirms the suitability of their use in phytostabilization processes.

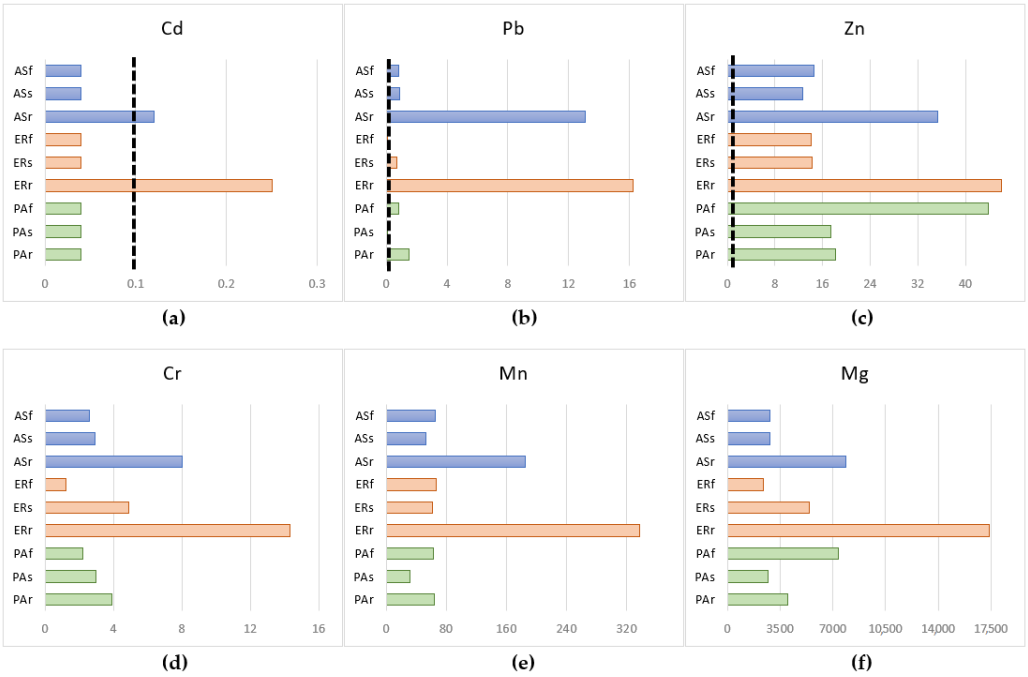


Figure 7. Content of potentially toxic elements (mg/kg) in individual parts of plants of the examined dominant species in Jelšava-Lubeník (Slovakia): (**a**) content of cadmium; (**b**) content of lead; (**c**) content of zinc; (**d**) content of chromium; (**e**) content of manganese; (**f**) content of magnesium (notes: ASf—*A. stolonifera* flower, ASs—*A. stolonifera* stem, ASr—*A. stolonifera* root, ERf—*E. repens* flower, ERs—E. repens stem, ERr—*E. repens* root, PAf—*P. australis* flower, PAs—*P. australis* stem, PAr—*P. australis* root,—limit value according to Act No. 220/2004 Coll. of Laws [54]).

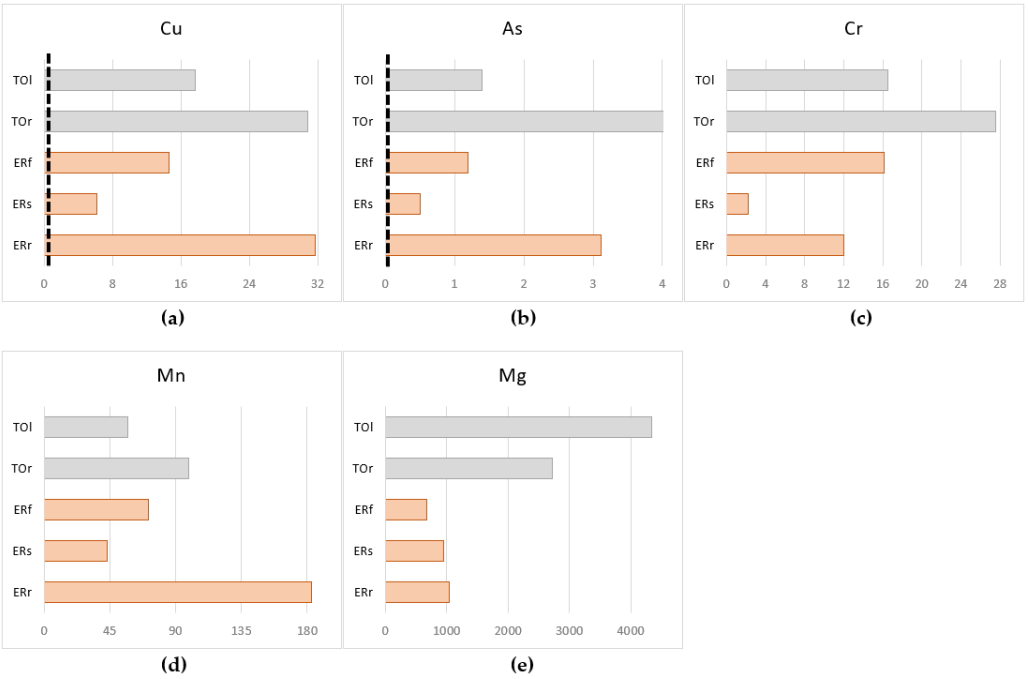
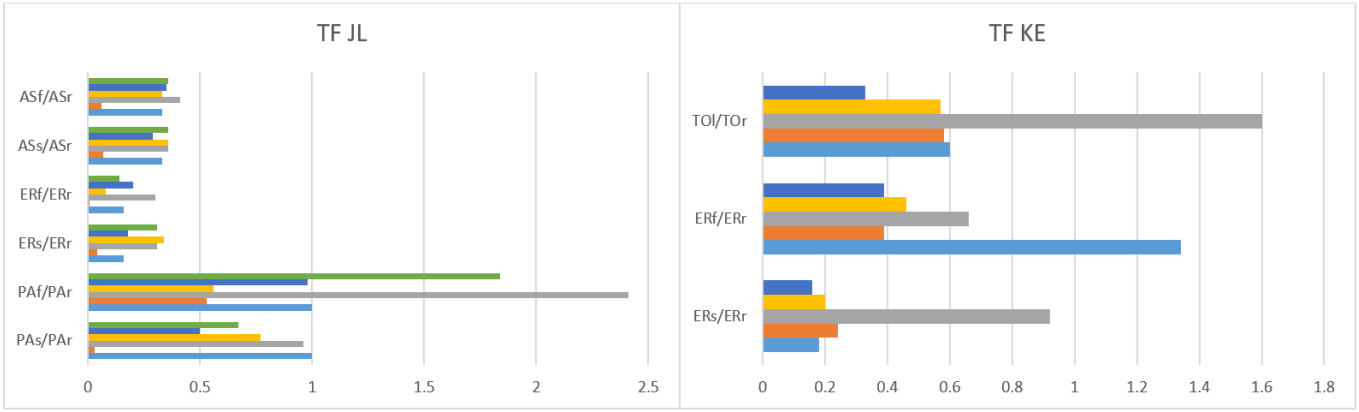


Figure 8. Content of potentially toxic elements (mg/kg) in individual parts of plants of the examined dominant species in Košice (Slovakia): (**a**) content of copper; (**b**) content of arsenic; (**c**) content of chromium; (**d**) content of manganese; (**e**) content of magnesium (notes: ERf—*E. repens* flower, ERs—E. *repens* stem, ERr—*E. repens* root, TOl—*T. officinale* leaf, TOr—*T. officinale* root,—limit value according to Act No. 220/2004 Coll. of Laws [54]).



(**a**) (**b**)

Figure 9. Translocation factor of investigated dominant plant species: (**a**) translocation factor for Jelšava-Lubeník; (**b**) translocation factor for Košice (notes: ASf—*A. stolonifera* flower, ASs—*A. stolonifera* stem, ASr—*A. stolonifera* root, ERf—*E. repens* flower, ERs—E. repens stem, ERr—*E. repens* root, PAf—*P. australis* flower, PAs—*P. australis* stem, PAr—*P. australis* root, TOl—*T. officinale* leaf, TOr—*T. officinale* root).

Our findings are also confirmed by the results of the principal component analysis (PCA) shown in Figures 10 and 11.

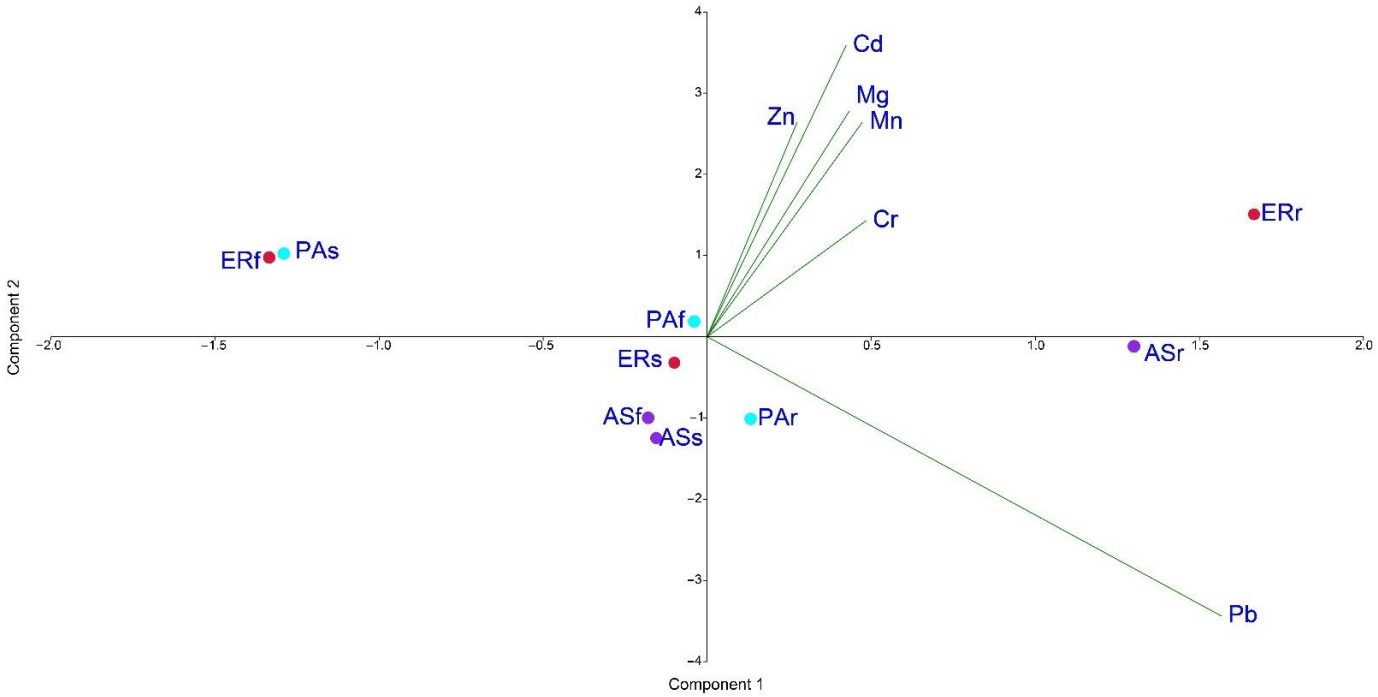


Figure 10. Principal component analysis (PCA) biplot of potentially toxic elements' concentrations and dominant plant species in Jelšava-Lubeník (Slovakia). Notes: ASf—*A. stolonifera* flower, ASs—*A. stolonifera* stem, ASr—*A. stolonifera* root, ERf—*E. repens* flower, ERs—E. repens stem, ERr—*E. repens* root, PAf—*P. australis* flower, PAs—*P. australis* stem, PAr—*P. australis* root.

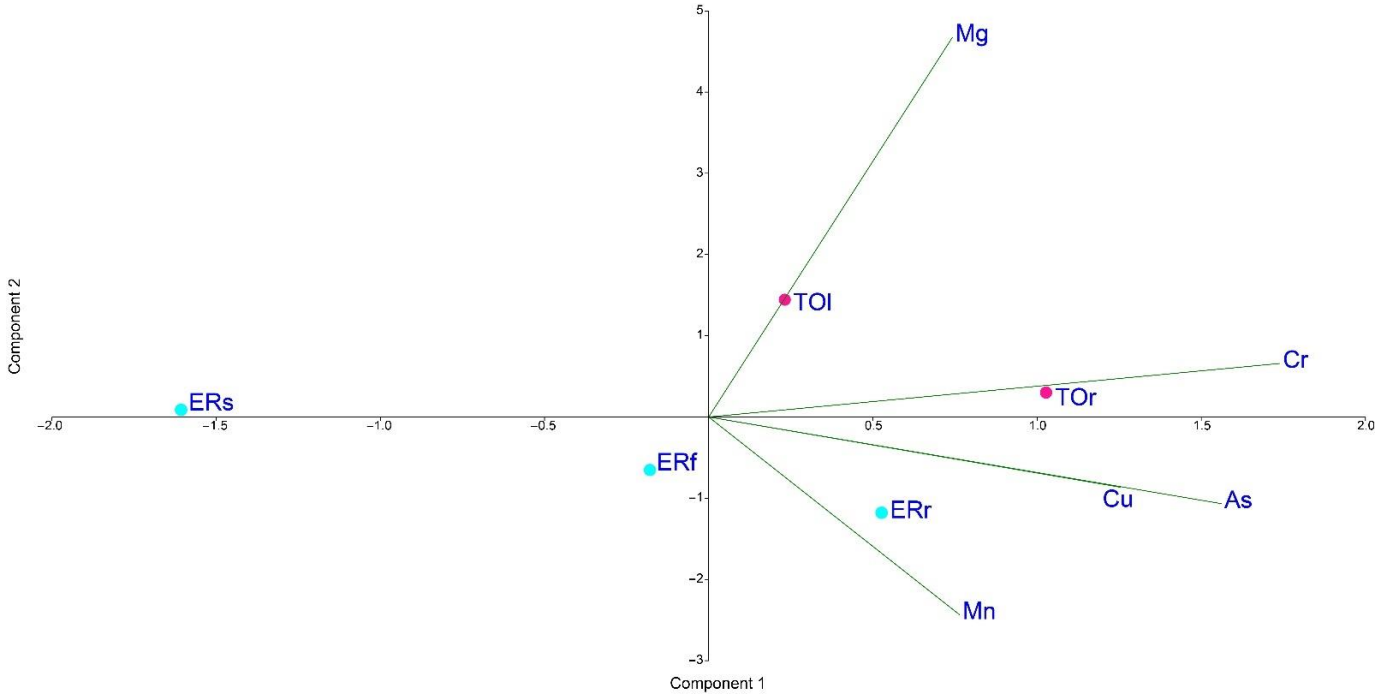


Figure 11. Principal component analysis (PCA) biplot of potentially toxic elements' concentrations and dominant plant species in Košice (Slovakia). Notes: ERf—*E. repens* flower, ERs—E. *repens* stem, ERr—*E. repens* root, TOl—*T. officinale* leaf, TOr—*T. officinale* root.

4. Conclusions

Experimental research was focused on the evaluation of the environmental risks of soil and plant contamination in two areas of magnesite mining and processing in the Slovak Republic. Based on the obtained results, it can be stated that:

- The soil reaction in the studied areas indicates a strong alkalization of the soil;
- Soils in the Jelšava-Lubeník area are significantly contaminated with Cr, As, Mn, and Mg. Based on the average I_{geo} values, the content of potentially toxic elements increases in the order of Mn < Hg < Fe < Pb < Ni < Cr < As < Cu < Zn < Mg < Cd. The most significant enrichment based on the average values of *EF* was found in the order of Cd > Mg > Zn > Cu > As > Cr > Ni > Pb > Fe > Hg > Mn. The observed C_f and C_d values indicate a high degree of soil contamination, mainly for Cd and Cr;
- In the territory of Košice, soils are significantly contaminated with Cr, Mn, Mg, and Ni. Based on the average values of I_{geo}, the content of potentially toxic elements increases in the order of Hg < Cr < Fe < Cu < As < Mg < Zn < Pb < Ni < Cd < Mn. The most significant enrichment was found in the order of Cd > Mn > Ni > Pb > Zn > Mg > Cu > As > Fe > Cr > Hg. Very high C_f was found for Pb and Cr;
- The results of correlation and hierarchical cluster analysis showed that high correlation coefficients and groups of associations between potentially toxic elements indicate a similar origin of pollution sources, which is caused by significant anthropogenic interventions due to magnesite mining and processing near industrial areas;
- The examined dominant plant species in environmentally polluted areas can accumulate high concentrations of monitored potentially toxic elements without more serious burden or damage. The results of the bioconcentration factor (*BCF*) and translocation factor (*TF*) confirmed that *P. australis* and *T. officinale* appear to be suitable accumulators in the phytoextraction process, as they can accumulate potentially toxic elements in the roots and at the same time transport them to the above-ground parts, especially Cd, Cr, and Mg. In the case of *E. repens* and *A. stolonifera*, it was confirmed that these species accumulate and immobilize high concentrations of poten-

tially toxic elements, especially in the roots, which confirms the suitability of their use in phytostabilization processes.

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